

A Roentgenographic Study of the Mechanics of Respiration

A DISSERTATION

Submitted in Partial Fulfillment of the Requirements of the
Degree of Doctor of Philosophy in the
University of Michigan

1935

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*Reprinted from SPEECH MONOGRAPHS,
(November, 1936), Vol III, No. 1*



A ROENTGENOGRAPHIC STUDY OF THE MECHANICS OF RESPIRATION*

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For the most part descriptions of the mechanics of respiration are vague both in concept and in terminology. In the hope of clarifying our own concept and providing a sound basis for an evaluation of the theories of controlled breathing, a detailed examination of the movements contributing to volumetric changes was undertaken. Roentgenographic studies were chosen as the medium of observation since they provide objective records of measurable accuracy, and a technique of examination not hitherto employed. The data for the discussion which follows has been gathered from an analysis of anteroposterior and lateral film studies of the thorax in maximum inspiration and maximum expiration.

The bony thoracic cage

Technique of measurement:

The technique of measurement of the extent of costal movement is a modification of that suggested by Fray,¹ in which the degree of costal mobility is measured by the change in amplitude of the costovertebral angle during respiration. The sides of this angle are formed by the axis of the vertebral column and the axis of the rib. By the use of a limb protractor it is possible to determine with considerable accuracy the change in angulation taking place between the extremes of inspiration and expiration. This angle variation further indicates the relationship of the lateral expansion and contraction of the thorax to the accompanying rib movement.

Findings:

It has been said that the first ribs do not move during quiet respiration.² However, measurement of the variation in angulation of the first rib pair in a series of film records of normal individuals indicates that these ribs are elevated and everted even during quiet respiration. During maximum respiratory effort the first ribs undergo extensive dis-

*A resume of the dissertation, *A Method of Determination of the Diaphragmatic Factor in Respiration*, completed under the direction of Professors J. H. Muyskens, C. B. Pierce, M.D., C. L. Meader, L. H. Strong, and G. E. Densmore, and submitted by the author to the faculty of the University of Michigan in June, 1935, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

¹Fray, Walter, "A Roentgenological Study of Pulmonary Ventilation," *American Journal of Roentgenology and Radium Therapy*, XXXIII (1935), 179-190.

²Gray, Henry, *Anatomy* (22d ed.) Philadelphia and New York: Lea and Febiger, 1930, 406.



placement. Angle measurements in ten cases show an average excursion of twenty degrees. Analysis of this excursion also reveals that there is not only a considerable movement of these ribs about a horizontal axis (that is, such that the anterior portion of the ribs describes an arc whose radius centers at the points of articulation with the vertebral column), but also that the lateral borders are elevated, demonstrating thereby a movement of the same character as succeeding ribs. (Wenkebach³ has noted that in some instances the first rib pair is elevated to an almost horizontal position during full respiration.) This suggests that Keith's⁴ conception of a 'thoracic operculum' formed by the union of the first ribs and the manubrium sterni is not wholly accurate.

By this technique of record and measurement certain other concepts of costal movement were found to be incorrect. Comparison of the costovertebral angle change in ten normal individuals demonstrates that on the average the second, and in the majority of cases either the second or the third ribs show the greatest degree of excursion during maximum respiratory effort, and that there is a gradual diminution of angle change from this level downward through the twelfth ribs. (MacLeod in discussing the undulatory movement of the ribs says, "The movement of each rib from above downward succeeds and exceeds that of the rib just above.")⁵ An assumption that the greatest degree of mobility is a characteristic of the long ribs of the lower costal series therefore becomes untenable. However, the arc described by the movement of a long rib with a lesser costovertebral-angle-variation may be larger than that of a short rib with greater variation in angle because of the greater radius. It is probably the latter fact which afforded the basis for MacLeod's statement that "the ribs, together with the sternal connections move through progressively increasing arches, and each lower rib tends to over-ride the rib just above."⁶ However, by comparison of the position of the axillary borders of the lung fields, as presented in frontal projections of the thorax in inspiration and in expiration, the actual disparity of these boundaries in the conical upper costal region is as great, and in many instances greater, than in the region of the lower ribs. The greater angle variation of the short ribs more than compensates for the greater length of the lower ribs.

³Wenkebach, K. F., "Ueber Pathologische lungs-und Thoraxformen," *Wiener Archiv fur Innere Medizin*, I-II (1920-21), 12-13.

⁴Keith, Arthur, "The Mechanism of Respiration in Man," *Further Advances in Physiology*, London: E. Arnold, 1909, 196-198.

⁵MacLeod, J. J. R. *Physiology in Modern Medicine* (7th ed.) St. Louis: C. V. Mosby, 1935, 337.

⁶*Ibid.*, 336.

In an interpretation of the movement of the upper costal series (second to fifth rib pairs) the displacement of the sternum during respiration is significant. By roentgenographic studies the sternum is shown to undergo during inspiration a definite upward and forward movement, consistent with the above description of the movement of the upper costal series. This observation confirms the statement of Keith⁷ that there is no such thing as a 'bucket-handle movement' of the upper ribs. (C. F. Hoover and other have used this term as descriptive of costal movement in the upper thorax.) Obviously, if these ribs were moved in the fashion of a bucket-handle there would be no anteroposterior displacement of the sternum. Furthermore, the longitudinal plane of the sternum is shown to remain at virtually the same angle with the vertical axis of the thorax at the extremes of inspiration and expiration, an added proof that the degree of costal movement does not increase in the direction of the longer ribs.⁸

This method of investigation has also provided information which alters former concepts of the role of the twelfth ribs during respiratory movements. Although it has been generally agreed⁹⁻¹⁴ that the twelfth ribs are either fixed, or actually descend during inspiration, our film records demonstrate that in every case the twelfth ribs showed a movement similar to that of the other ribs although the amplitude of angle variation was smaller.

The muscular elements of the thoracic cage:

From such observations of costal movement it is possible to draw certain inferences regarding the muscular activity that produced these changes. The movement of the first and second rib pairs during normal respiration and their extensive movement during maximum respiration have been noted above. Since the only groups of muscles that can cause the rotation in elevation described are the *scaleni*, we must conclude that their activity in this role is an important part of their function. By this action the *scaleni* contribute to the expansion of the apical portion of the lungs. (C. F. Hoover, among others, has regarded the function of the *scaleni* as being solely "to form a point of fixation

⁷Further Advances in Physiology, 205.

⁸MacLeod, *loc. cit.*

⁹Briscoe, Charlton, "Lumleian Lectures," *Lancet* 1(5404), (1935), 637-42.

¹⁰Gray's *Anatomy*, 405.

¹¹Keith, *Further Advances in Physiology*, 202.

¹²Landois-Sterling, *A Manual of Human Physiology* (3rd American trans. from 6th German ed.), Philadelphia: P. Blakiston, Son, and Co., 1889, I, 240.

¹³MacLeod, *Physiology in Modern Medicine*, 337.

¹⁴Starling, Ernest H., *Principles of Human Physiology* (6th ed.) London: J. & A. Churchill, 1933, 901.

in the first ribs from which the second, third and fourth ribs are elevated.")¹⁵

The question of the action of the intercostal muscles is answered in some degree by observations of patients in whom intercostal neurectomy has been employed in the treatment of pulmonary tuberculosis.¹⁶ Definition of cause and effect in these instances may be complicated by the section and consequent disfunction of the *levator costarum*, *serratus posticus superior*, and the *scaleni*. However, comparative inspiration-expiration films of the thorax made before and after operation show that the costal movement on the affected side is significantly reduced. Inasmuch as the reduction in costal movement is found to be identical with the intercostal muscles paralyzed (that is, if the first through the eighth intercostal muscles are paralyzed, there is a reduction in movement of the second through the ninth ribs) it may be logically assumed that the intercostal muscles play a part in the elevation and depression of the ribs. No information as to the antagonism usually assumed to exist between the internal and external intercostals has been obtained in this study.

It has already been noted that the twelfth ribs move upward during inspiration and downward during expiration. Since the *quadratus lumborum* is the largest muscle which can conceivably bring about the downward shift of these ribs, we may conclude that it acts not as an inspiratory muscle, but rather as an expiratory muscle. By reason of the direction of pull exerted by the *serratus posticus inferior* one may conclude that it assists in this action. Since the twelfth ribs form points of attachment for the posterior portion of the diaphragm, it may be concluded further that the *quadratus lumborum* can assist in the downward movement of the diaphragm during inspiration only insofar as it may act in tonus to resist the pull of the posterolateral portion of the diaphragm on the twelfth ribs.

The Diaphragm:

The factors discussed above are those contributing to the antero-posterior and lateral expansion of the thorax during respiration. The major increase in the vertical diameter is brought about through the contraction of the diaphragm. This muscle has been widely discussed in its relationship to breath control as a significant factor in voice production. The current confusion in descriptions of its form and movement is unfortunate.

¹⁵Hoover, C. F., "Diagnostic Signs from the Scaleni, Intercostal Muscles and the Diaphragm in Lung Ventilation," *Archives of Internal Medicine*, XX (1917), 701-15.

¹⁶Alexander, John, "Multiple Intercostal Neurectomy for Pulmonary Tuberculosis," *American Review of Tuberculosis*, XX (1929), 637-84.

The term 'dome' as used to describe the form of the diaphragm is permissible only when applied to the hemidiaphragm. The contour of the diaphragm as seen in frontal roentgenographic projections of the thorax does not form a simple curve, but is marked by a median depression which traverses it from before backward, dividing the diaphragm therefore into the hemidiaphragms, or right and left domes, of unequal height. The apex of the right hemidiaphragm ordinarily stands somewhat higher than the left, the usual difference being about two centimeters.

With the contraction of the diaphragm the radius of curvature of each dome is perceptibly increased, accentuated by the associated increase in the transverse and anteroposterior diameters of the thorax during inspiration. The contraction of the diaphragm in deep inspiration may not result in the degree of flattening that is supposed to accompany this movement. Rarely, if ever, can it be demonstrated that the phenomenon of 'flattening' is the most significant factor in the increase in pulmonary volume contributed by diaphragmatic contraction. The downward and forward excursion of the major portion of the diaphragm in contraction reduces the difference between the two domes and the median depression. The hemidiaphragms are still distinguishable at the maximum of deep inspiration.

The principal increase in the vertical diameter is to be found in the posterior thorax associated with the greater forward and downward contraction of that portion of each hemidiaphragm. Hitzenger¹⁷ has noted cases in which the frontal roentgenogram of the thorax showed an apparent upward movement of the entire diaphragm upon inspiration whereas the lateral view demonstrated an extensive downward movement of the posterior portion of the diaphragmatic shadow. This condition is easily explained as an elevation of the small sternal portion of the diaphragm with respiration of a pronounced costal type. This explanation may also apply in cases in which the excursion of the hemidiaphragms is small as seen in the frontal projection of the thorax. The suspension of the liver may permit in some instances only a restricted movement of the anterior portion of the diaphragm.

The measurements of diaphragmatic movement usually quoted give the absolute range of movement for the right hemidiaphragm as 34 mm. and for the left 32 mm.¹⁸ In some cases which I have examined excursion of as much as six or seven centimeters was the result of maximum respiratory effort. Hitzenger records having observed one

¹⁷Hitzenger, Karl, *Das Zwerchfel im Gesunden und kranken Zustand* (Wien, 1927), 34.

¹⁸Dally, J. F. Halls, "A Contribution to the Study of the Mechanism of Respiration," *Proceedings, Royal Society*, London: Series B, LXXX (1908), 182-87.

case in which there was an excursion of nine centimeters. In normal respiration the movement is considerably less, the average excursion being in the neighborhood of one to two centimeters.

Volumetric determinations:

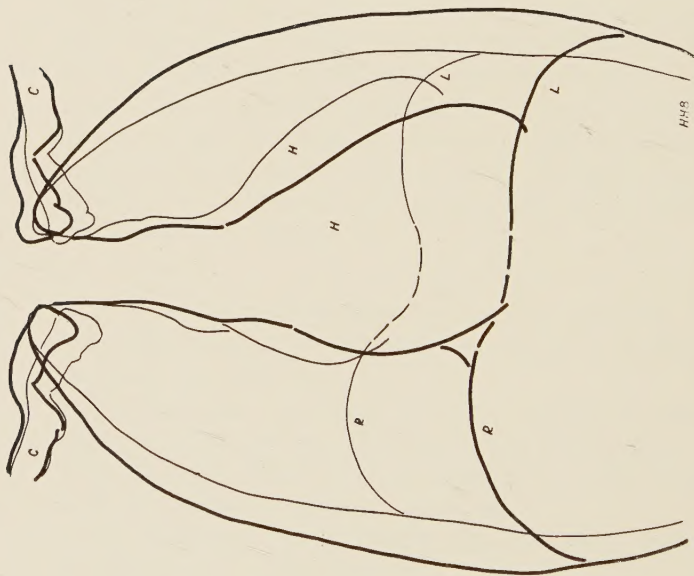
In this investigation a method of evaluating the factors of vertical, anteroposterior and lateral expansion of the thorax in relation to the consequent changes in pulmonary volume was developed. Computations directed toward an estimate of the total volumetric significance of the diaphragm, included reference to the complex movement of the thoracic walls in expansion and reduction of the transverse and anteroposterior diameters of the thorax. Because of the individually variable phrenic movement described above it was necessary to use lateral projections of the thorax in all calculations of thoracic volume, and especially in computing the diaphragmatic component.

In this study it was found that calculations using factors of costal movement (as indicated by costovertebral angle change) and diaphragmatic excursion permitted an evaluation of the contribution of diaphragmatic movement to the vital capacity. In the ten cases measured the diaphragmatic excursion contributed on an average forty-three per cent of the vital capacity, although the percentages in the individual cases ranged from twenty-nine to sixty-three per cent. (The percentage indices on the ten cases were as follows: 29, 33, 36, 42, 43, 45, 46, 55, 63.) Obviously a series of ten cases is not sufficiently large to give more than an indication of the significance of the part played by the diaphragm in maximum respiratory movements. It is of interest that in seven of the ten cases the volume change estimated to have been contributed by diaphragmatic action exceeded forty per cent of the vital capacity.

SUMMARY

1. The roentgenographic technique used in measuring the costovertebral angle change is a dependable method of evaluation of the costal movement in respiration.
2. The first ribs have been found to undergo movement similar in character to that of the other ribs during respiration.
3. The average degree of costal mobility has been shown to decrease from the second or third ribs downward.
4. The movement of the twelfth ribs was found to be of the same character as that of the other ribs.
5. The plane of the sternum remains at virtually the same angle with the vertical axis of the thorax at the extremes of inspiration and expiration.
6. The *scaleni* are active in elevating the first ribs.

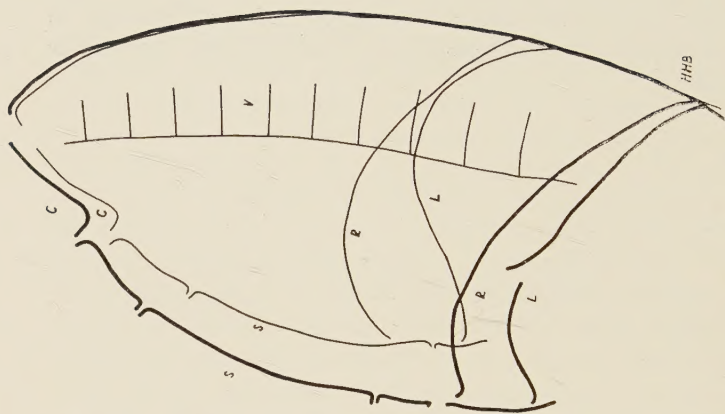
7. Dysfunction of the intercostal muscles is accompanied by a reduction in the respiratory excursion of the corresponding ribs.
8. Evidence indicates that the *quadratus lumborum* acts as a muscle of expiration, drawing the twelfth ribs downward.
9. The excursion of the diaphragm is significant in volumetric changes of the thorax. The volume changes attributable to the diaphragm in ten cases ranged between twenty-nine and sixty-three per cent of the vital capacity.



SKIAGRAM OF ANTEROPOSTERIOR PROJECTION OF THORAX

The vital capacity of this subject was 4000 c.c. The vertical displacement of the hemidiaphragms was approximately 6 centimetres, 1450 c.c. is estimated to have been the volume contributed by diaphragmatic movement. Note that linear displacement of diaphragmatic shadows is greatest in the forward-downward rather than in vertical directions as shown in lateral projection.

C—clavicles; R—right hemidiaphragm; L—left hemidiaphragm; H—heart; ——— Inspiration; ——— Expiration; S—sternum; V—vertebral column.



SKIAGRAM OF LATERAL PROJECTION OF THORAX

